AFRL-SR-AR-TR-09-0272

# REPORT DOCUMENTATION PAGE



| | | |
|---|---|---|
| **1. REPORT DATE** *(DD-MM-YYYY)* 30-05-2009 | **2. REPORT TYPE** Final Report | **3. DATES COVERED** *(From - To)* 01-03-2008 - 31-03-2009 |
| **4. TITLE AND SUBTITLE** Distributed Atmospheric Neutral Density Explorer (DANDE) | | **5a. CONTRACT NUMBER** |
| | | **5b. GRANT NUMBER** FA9550-07-1-0261 |
| | | **5c. PROGRAM ELEMENT NUMBER** |
| **6. AUTHOR(S)** Chris Koehler, Lee Jasper, Kyle Kemble | | **5d. PROJECT NUMBER** |
| | | **5e. TASK NUMBER** |
| | | **5f. WORK UNIT NUMBER** |
| **7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)** Colorado Space Grant, University of Colorado, 520 UCB, Boulder, CO 80309-0520 | | **8. PERFORMING ORGANIZATION REPORT NUMBER** |
| **9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)** Dr. Kent Miller, AFOSR/NE, 875 N. Randolph St., Suite 3112, Arlington, VA 22203, (703) 696-8573 | | **10. SPONSOR/MONITOR'S ACRONYM(S)** |
| | | **11. SPONSOR/MONITOR'S REPORT NUMBER(S)** |

**12. DISTRIBUTION / AVAILABILITY STATEMENT**

Distribution A: Approved for Public Release

**13. SUPPLEMENTARY NOTES**

**14. ABSTRACT**

Within the past 14 months the DANDE project has progressed significantly. January through April of 2008 consisted of preparation for CDR where primary modeling and design of the major components for DANDE were completed. A vibration test had also occurred in March 2008 which showed promising results, however the structure had to be stiffened at all axes. The months of May through August 2008 were spent completing FlatSat revisions of electronics and flight structural components. September through December 2008 was spent creating flight and near-flight components. The satellite was then integrated and basic functionality was achieved for all subsystems. January 2009 was spent preparing for FCR, which was won by the DANDE team and a flight was secured for the project. February through March 2009 were months focused upon less developed subsystems such as software and communications, which have made notable progress within that time.

**15. SUBJECT TERMS**

| **16. SECURITY CLASSIFICATION OF:** | | | **17. LIMITATION OF ABSTRACT** | **18. NUMBER OF PAGES** | **19a. NAME OF RESPONSIBLE PERSON** Chris Koehler |
|---|---|---|---|---|---|
| **a. REPORT** | **b. ABSTRACT** | **c. THIS PAGE** | | | **19b. TELEPHONE NUMBER** *(include area code)* 303/492-3141 |



20090904430

# Drag and Atmospheric Neutral Density Explorer (DANDE)

## 1. Background

Drag induced by the neutral-atmosphere is the major perturbation on satellites in LEO. Models exist to account for large scale temporal and spatial variations in the density of the atmosphere but do not account for the small-scale wave structures or their dynamics. Furthermore, true density deviates as much as 20% from model predictions [1], introducing error into precise orbit determination and tracking operations. Because these operations are crucial to the Air Force and NASA, a need exists to quantify density variations, and to provide in-situ model density and wind calibration data [2], especially at lower altitudes (around 350 km) where such data is nonexistent as shown in Figure 1.

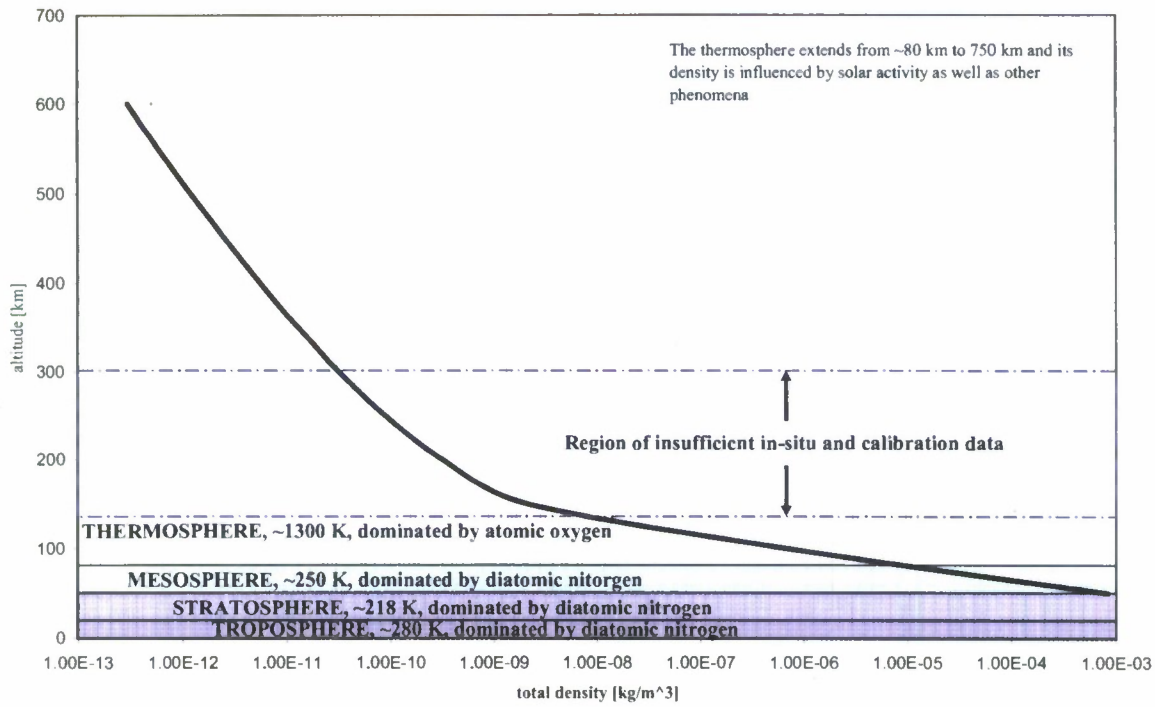



**Figure 1: Density and composition of atmospheric regions [3]**

The Drag and Atmospheric Neutral Density Explorer (DANDE) shown in Figure 2 will be a density, wind, and composition sensor that will provide data for the calibration and enhancement of models, improve our understanding of the thermosphere, and demonstrate novel measurement technologies. DANDE is a part of AFRL's University Nanosat Program (UNP). DANDE was selected as the winning satellite from a national competition with 10 other universities to build and test a working satellite. DANDE will be placed in a LEO orbit as a mission of opportunity and will contain accelerometers and a wind sensor. As DANDE's orbit decays due to atmospheric drag, it will have the opportunity to study drag at various altitudes. DANDE will provide timely daily-average and in-situ data for calibration and thermospheric analysis over a span of 100 days.

To achieve its goals, DANDE will make measurements at altitudes between 200 km and 350 km using spacecraft radar tracking and two on-board instruments. Tracking will be done through a collaborative agreement with Air Force Space Command Space Analysis (AFSPC) A9A which will provide high-priority precision tracking for drag.

**Figure 2: The DANDE spacecraft showing solar cells (blue).**

In order for DANDE to be operationally useful as a drag measuring device and tracking-target, it must be near-spherical.

DANDE was designed and built at the Colorado Space Grant Consortium (COSGC) in collaboration with the University of Colorado at Boulder Aerospace Engineering Sciences department, AFSPC A9A, and research faculty at the National Oceanic and Atmospheric Administration (NOAA) along with an instrument partnership with NASA Goddard. As DANDE enters the second phase of its program, students will be completing the software and testing on a system and subsystem level in preparation for spacecraft delivery to AFRL in late 2009.

### 1.1. Calibration of Present Models, Near-real Time Space Weather Updates

The Air Force HASDM operation makes use of a set of approximately 80 satellites at various altitudes to obtain near-real time updates for a calibrated global density model. While the in-situ measurements described in section 3.1 will lead to model validation and improvement, radar tracking data will be able to provide average density values once to several times each day. This data is especially important for HASDM at lower altitudes where the DANDE satellite will be deployed. The spherical nature of the sphere allows for even better density determination as the attitude does not introduce uncertainties into the density measurements by varying the effective cross sectional area or the coefficient of drag. Although Space Command is unable to provide the Colorado team with the raw tracking data, it has been agreed that processed density and orbit information from high-priority tracking will be disseminated along with the fitted drag coefficient. The Colorado team will be able to use this information to evaluate calibration and data assimilation techniques and to complement the in-situ data. In addition to HASDM the team will also evaluate the new HWM07 Horizontal Wind Model.

### 1.2. Experimental Equipment

#### 1.2.1. Low Altitude In-Situ Accelerometer Data

In-situ density data may be obtained from acceleration measurements by using the relations expressed in the following equation

$$a_{drag} = \frac{1}{2} C_d \frac{A}{m} V_i^2 \rho \qquad \textbf{Equation 1}$$

where $C_d$ is the coefficient of drag, $A$ is the effective surface area, $m$ is the mass of the spacecraft, $V_i$ is the in-track component of the spacecraft velocity with respect to the atmospheric velocity or wind, and finally $\rho$ is the atmospheric density. The GRACE accelerometers provide accelerations with a resolution of $1 \times 10^{-10}$ m/s$^2$ but are unable to distinguish between acceleration changes due to density variation from those due to atmospheric wind velocity. This problem is especially relevant during geomagnetic storms when wind velocities can be as high as 2 km/s. For drag measurements, the spacecraft should have a well determined cross sectional area and coefficient of drag. A sphere has a cross sectional area and a coefficient of drag that do not vary with attitude and is ideal for this kind of experiment. Finally, the determination of density is also sensitive to the errors in determining velocity as this component of equation 1 is squared. The DANDE design will address all these problems in the measurement and characterization of density as described in sections 1.2.2 and 3.1.

Scientific and precision-control missions often need to measure accelerations to sub μg levels in order to quantify the non-gravitational forces acting on the spacecraft. The resolution of MEMS accelerometers has a cut-off at about 1 to 0.5 μg and cost in the thousands to tens of thousands of dollars. In contrast, accelerometers which employ an electro-statically constrained proof-mass, can achieve resolutions of almost a pico-g and the starting cost is several million dollars. The lack of medium-resolution, medium-cost, and space-worthy acceleration sensors poses a significant difficulty to low-cost missions. Not all missions require the resolution of the more expensive accelerometers and a resolution above 1 nano-g is adequate to measure the most significant non-gravitational perturbations in LEO. The development of a low-cost, high-resolution acceleration measurement scheme that fills the gap in currently available sensors would open up the design space and lower the cost of obtaining precision science and control for many missions. DANDE uses off-the-shelf accelerometers along with a novel bias-removal and error-processing technique to accomplish this goal.

The accelerometer subsystem is composed of six independent accelerometer sensor heads and filtering electronics and software on board the spacecraft. The six sensor-heads are Honeywell QA-2000 sensors and their outputs are fed into independent band pass filters and processing software. As DANDE spins, these sensor heads are rotated into and out of the ram direction. This achieves a modulation of the drag signal into a precisely known frequency regime and allows for filtering out of other frequencies thus reducing the total integrated noise of each sensor head. These signals are then processed further and averaged onboard to produce a single acceleration value. The benefit of having six accelerometers is first to reduce the overall noise by $1/\sqrt{6}$ and second to allow the system to degrade gracefully. Another great aspect of this method is that by rotating each sensor head into and out of the drag direction, sensor bias is effectively removed.

**Figure 3: The accelerometer subsystem.**

### 1.2.2. Wind and Composition Measurements

Several other observation satellites and missions have attempted to measure accelerations created by the atmosphere. However none have been able to differentiate between density accelerations and wind accelerations. Atmospheric density is the primary contributor to satellite orbit changes and decay. Differentiating between these two sources of accelerations is pivotal to understanding the atmospheric conditions and their affects on satellites.

The DANDE spacecraft will be able to observe wind velocity magnitudes from the in-track and cross-track directions. The observability of both density and wind speed is due to the fact that accelerometer measurements are proportional to the square of the velocity while mass spectrometer readings are proportional to the inverse of the velocity [4]. DANDE's onboard Neutral Mass Spectrometer (Figure 4) will measure the energy and angular distribution of the incoming particles, enabling a determination of in-track and cross track winds.

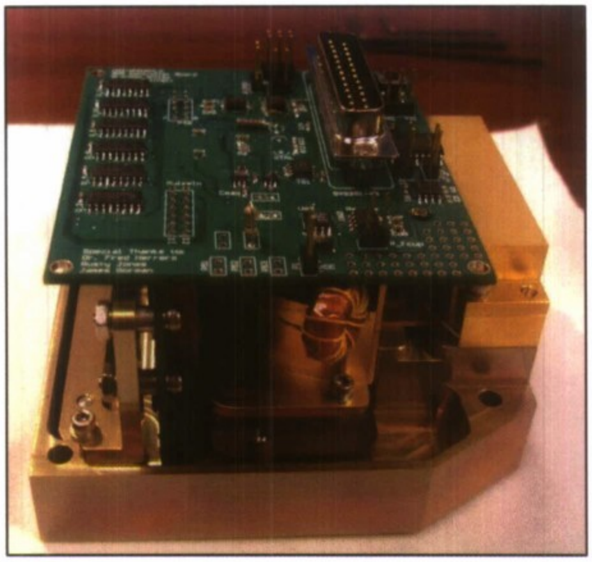


**Figure 4: The DANDE Neutral Mass Spectrometer.**

### 1.3. Orbital Range

In order to properly achieve the science objectives of the DANDE mission, the proper orbital parameters must be achieved. Since little information is known about the 350km to 200km range of the atmosphere, DANDE must reach this height during some part of its orbit, if not the entire time. Two orbits bound the best and acceptable cases for the DANDE mission. The first orbit could be a circular sun-synchronous noon-to-midnight orbit at an altitude of 350 km, which could meet requirements while being able to access the ground station in Boulder, Colorado. The second orbit could be an elliptical orbit with an apogee altitude of 1200 km and the perigee at 200 km. This is not an ideal case because DANDE would only be able to collect data at perigee and a second ground station would be necessary. DANDE's orbit inclination must stay above 40 degrees latitude to allow for the Boulder ground station to be the primary data downlink center however, the mission requires that DANDE stay above 60 degrees latitude to gain the best observation of effects of the sun on the atmosphere. High inclinations are ideal.

### 1.4. CONOPS

To ensure that the DANDE mission succeeds, there have been several key concept of operation (CONOPS) details identified. These steps and procedures which have been designed to be intrinsic to the mission have been developed through the CONOPS.

DANDE has been designed to optimally be in a circular orbit starting at about 350km in altitude with a near polar orbit. It has also been anticipated that the most scientifically relevant data will be collected near solar maximum, which should peak around the year 2012. The mission has been designed to span the duration of 100 science gathering days even though the satellite may remain in orbit for longer than 100 days. This duration has been set to allow for DANDE to hopefully experience about five solar events which cause significant increase in density.

After the desired orbit as described above has been achieved, the satellite disengages from the launch vehicle. Because of DANDE's spherical shape it required adaptors to the launch vehicle, which were not circular, to provide the desired interface. The DANDE satellite system was designed with a sphere and the Lightband Adapter Bracket (LAB). This configuration, as shown in Figure 5, is designed to be compatible with the Planetary Systems Lightband deployment ring as well as the Expandable Secondary Payload Adapter (ESPA) interface.

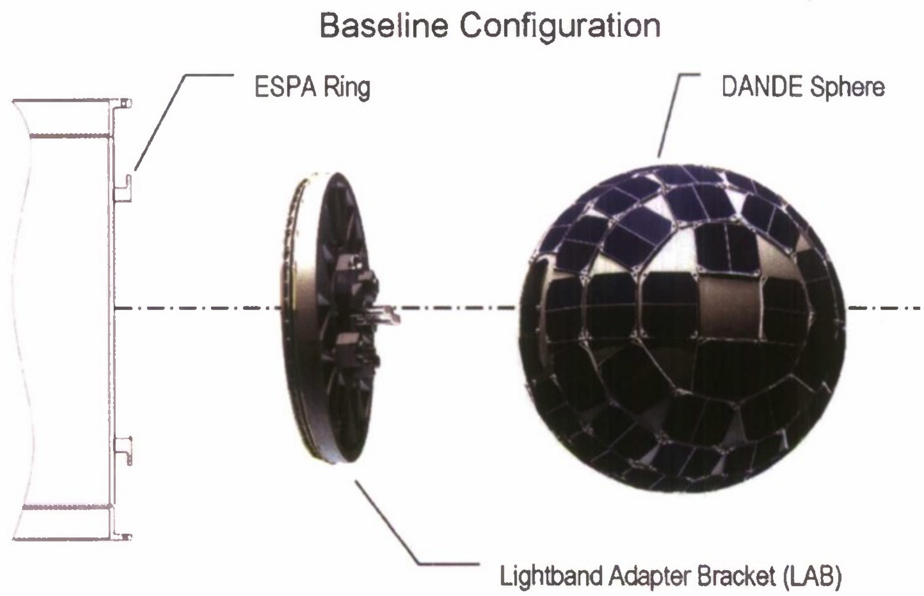
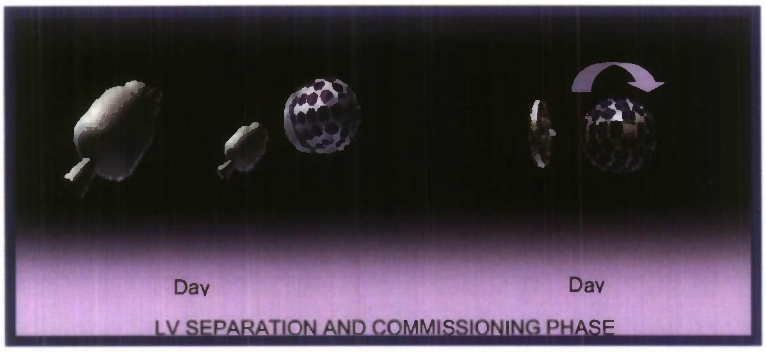



**Figure 5: The DANDE configuration.**

After launch, DANDE has been designed to drop the launch vehicle adaptor post launch vehicle separation as shown in Figure 5 and Figure 6. Once successful separation has completed, DANDE shall continue to its spin up maneuver and maintain contact with the ground station to download data and upload commands and sequences, also shown in Figure 6.




- Phase 1: LV Separation and commissioning
  - Launch Mode - time delay – Safe Mode
  - Full charge and checkout [18 – 30 hours]
  - Lightband jettison

- Phase 2: Attitude Acquisition
  - Spin Up [24 h]
  - Spin-Axis Alignment

- Phase 3: Science [~90 days]
  - Science Mode
  - Standby Mode
  - Comm. Pass

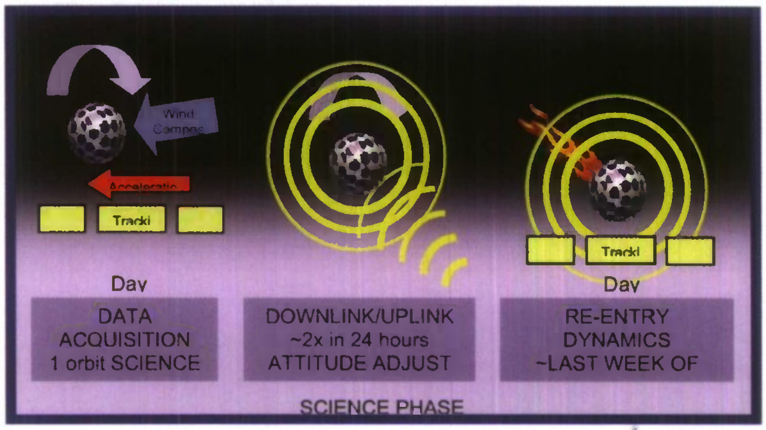



**Figure 6: Mission Timeline**

The spin of DANDE provides two key advantages for the mission: stabilization and an accelerometer data acquisition method. The stabilizing effects of the spin have been shown to allow DANDE to point in the correct direction for the mass spectrometer sampling. The spectrometer has a small aperture which needs to be pointing within 10 degrees of the spacecraft's ram direction. Stabilization also allows for more consistent antenna gain patterns for ground station use. The second reason for spinning has been developed to allow for the navigation grade accelerometers to measure micro-g accelerations while effectively zeroing offsets as described in Section 1.2.1.

Several operational modes were created to aid the mission. The science mode collects data using the two instruments onboard. Due to power constraints, this mode cannot always be in operation. Safe mode stops all activity on the satellite and keeps it in stand-by where it waits for ground operator contact and intervention. This mode will occur during off nominal health and status updates detected by the satellite. Alignment mode was also designed to allow the spacecraft to align properly with the ram vector for the mass spectrometer. Several other modes exist like the spin up maneuver, and launch mode however these only occur one time throughout the duration of the mission.

Communications has been another major piece of the CONOPS for DANDE. The system runs at 9600 baud and two ground stations will be used to allow for enough data to be downlinked. One ground station will be in Boulder, Colorado while the other, in San Juan, Puerto Rico.

## 2. Published Paper Synopsis

Within the last year, four Masters Theses have been completed concerning the DANDE program. There have also been three papers published at different conferences. While the papers have mostly dealt with displaying the

DANDE mission and unique science, the theses have made direct contributions to the engineering development of DANDE.

## 2.1. Theses

### 2.1.1. Communications

The basic communications subsystem design was created by Diana Loucks and was outlined within her thesis *Communications Systems Engineering for the Drag and Atmospheric Neutral Density Explorer.* While the entire subsystem design is documented, the primary focus of efforts in the design process was on the antennas as they were the only components that were completely dependent upon the shape and size of the spacecraft. The method for science data collection dictated that the structure maintain its spherical shape with minimal faceting or protrusions to ensure validation of science data. The DANDE communications subsystem takes advantage of this required spherical shape to increase the efficiency and coverage of the quarter-wave shorted patch antenna for both transmit and receive. While initial designs produced antennas with only 30% efficiency and 10 dBi peak gain, analyses conducted over variations of antenna dimensions, substrate dimensions and substrate electrical properties indicate that changing the substrate material and fixing dimensions for the antennas as well as the substrate will yield antennas with efficiencies near 70% and a peak gain near 0dBi.

The design process for the electrical components began with the analysis of three primary heritage systems and concluded with the selection of commercial off-the-shelf (COTS) equipment modified for DANDE's requirements. The combination of the COTS equipment with the optimized quarter-wave shorted patch antennas provide the framework for a down-link data rate of 38,400 bits per second (bps), and an up-link data rate of 9,600 bps. Link budget analyses performed for worst-case scenarios periodically throughout the design process indicate positive margin on both the up and down-links. These results indicate that the DANDE Communications subsystem will meet mission requirements throughout the satellite's lifetime.

This thesis is attached to the end of this report.
Loucks, D., Communications Systems Engineering for the Drag and Atmospheric Neutral Density Explorer, Master's Thesis, U. of Colorado, Boulder, CO, 2008

### 2.1.2. Operations

DANDE's orbital envelope and operations plan was created by Marcus Wilde in his thesis *Mission Operations and Simulation for the DANDE spacecraft.* Based on mission objectives and system requirements, existing orbital lifetime analyses were refined, using a more detailed model for altitude-dependent drag coefficients and predicted values for solar activity levels in the 2012 timeframe, when DANDE is intended to be launched, in order to derive orbital envelopes both for minimum required spacecraft performance and for maximum mission success. The history of Space Test Program flights were then analyzed for missions that were launched into DANDE's orbital envelope in order to assess the probability of future launches targeting this range of orbit geometries. The extreme cases of the orbital envelope were then analyzed concerning data budget, in order to determine whether multiple ground stations will be necessary to accomplish mission objectives. This led to a selection of orbits and ground stations to be used in the Design Reference Mission. Also, a spacecraft tracking and orbit prediction simulation was conducted in order to verify tracking requirements.

These analyses resulted in two orbital cases to be used for definition of operation modes and the Design Reference Mission and show that a variety of launch opportunities may be available for these orbits. Orbital case one is a circular sun-synchronous noon-to-midnight orbit at an altitude of 350 km, meeting all orbital requirements and goals using the Colorado Space Grant ground station in Boulder, Colorado; case two is an elliptical orbit with an apogee altitude of 1,200 km and the perigee at 200 km. A mission on this orbit meets all minimum requirements if run with one additional ground station, for simulation purposes chosen to be the Hawaii Space Grant station in Manoa, Hawaii. System Modes Definitions were then provided for both orbital cases, defining subsystems' activities throughout the mission, leading to the Design Reference Mission giving an operational plan for the whole mission from launch to re-entry, focusing on positive power and data budgets for analyzing compliance to mission requirements.

This thesis is attached to the end of this report.
Wilde, M., Mission Operations and Simulation for the DANDE Spacecraft", Master's Thesis, Lehrsuhl fur Raumfahrttechnik, Munich, Germany, 2008

### 2.1.3. Attitude Control System

The spin up and attitude control of DANDE was developed in the thesis *Design and Specification of an Attitude Control System for the DANDE Mission* by Brady Young. The paper emphasizes three major tasks: an architecture trade study, an analysis of the spin up maneuver, and a demonstration of the attitude determination method.
This document follows the systems engineering process used to design the ADC subsystem in the context of the Drag and Atmospheric Neutral Density Explorer (DANDE) mission. A number of missions relevant to the design of the DANDE spacecraft were reviewed. Some missions were similar to DANDE in their design constraints (e.g., student satellites), others served as examples of successfully implemented design decisions.

A subsystem architecture trade study was then performed, leading to the key design decisions in the ADC subsystem: DANDE would be a major-axis spinning spacecraft, spinning at 10 RMP about the orbit normal vector. DANDE will attain its required spin rate in a closed loop algorithm and will be aligned open loop. DANDE will determine partial attitude using a magnetometer during spin up, then full spin axis determination will be accomplished using Horizon Crossing Indicators. Active control shall then be performed using magnetic torque rods, and nutation will then be passively damped with a fluid-filled ring.

An attitude simulation program was designed and implemented in MATLAB. This model was used to perform an analysis of the spin up maneuver, demonstrating that the subsystem will be capable of spinning up the spacecraft from an unknown initial state within the time required. A baseline algorithm was tested, then refined to mitigate conditions that could prevent spin up from completing within the budgeted time.

To validate requirements on the attitude determination hardware, a spin axis determination scheme was presented, and a worst-case analysis performed. The study generated a reference attitude profile in software, modeled the sensor response to the environment, and calculated the determined attitude. This was compared against the reference attitude and used to find the minimum quantity of sensor data needed to meet the attitude determination requirements.

This thesis is attached to the end of this report.
Young, B., Design and Specification of an Attitude Control System for the DANDE Mission, Master's Thesis, U. of Colorado, Boulder, CO, 2008

### 2.1.4. Error Investigation

The final thesis, written by Marcin Pilinski, dealt with collecting data from DANDE and was titled *Analysis of a Novel Approach for Determining Atmospheric Density from Satellite Drag.* Often, during satellite monitoring of the thermosphere, in-track winds are not measured and spacecraft have usually not had constant drag coefficients. DANDE will have the capability to study in-situ winds, composition, and density while having a constant drag coefficient. To address these in-situ measurement issues in the context of a case study, analysis and error modeling will be applied to the Drag and Atmospheric Neutral Density Explorer (DANDE) and its instruments.

A method was presented which could serve as an error analysis of the measurements and which could be extendable to other in-situ missions with similar instruments in order to ascertain the fidelity of this and other measurement concepts. The method included the modeling of the spacecraft and its instruments, the input from the ambient environment, on-board data analysis, and gas-surface interactions causing the measured forces on the spacecraft.

In the course of the analysis, it was demonstrated that DANDE would meet its required measurement fidelities and that the secondary reactions caused by the solar cells/ particle interaction on the spacecraft are a small contribution to the drag coefficient and cause a relatively low uncertainty in drag compared to other spacecraft. It is also shown how physical drag and drag coefficients could be calculated.

This thesis is attached to the end of this report.
Pilinski, M., Analysis of a Novel Approach for Determining Atmospheric Density from Satellite Drag, Master's Thesis, U. of Colorado, Boulder, CO, 2008

### 2.2. Papers

Marcin Pilinski also published a paper to the AIAA titled *An Innovative Method for Measuring Drag on Small Satellites*. This paper discussed the need to accurately predict satellite positions which continues to be a leading aspect of space situational awareness and presents increased challenges in the specification of the spacecraft environment in low earth orbit. Atmospheric drag has been shown to be the most important environmental perturbation for low orbiting spacecraft and the most difficult one to model and predict precisely. The paper presented method for the characterization of satellite drag through the use of a dual-instrument in-situ approach. Both the accelerometer and Neutral Mass Spectrometer instruments were discussed. A sophisticated error model was then discussed which has been developed to evaluate this method and the results show that it maybe possible to improve the ability to characterize satellite drag by at least 10-14%. The paper described the measurement process, as well as a method of computing the satellite drag coefficient. Finally, the paper discussed ground testing of the instruments which has indicated that the instrument hardware will meet the requirements necessary to produce an improved data product.

This paper is attached to the end of this report.
Pilinski, M., An Innovative Method for Measuring Drag on Small Satellites, 22nd Annual AIAA/USU Conference on Small Satellites, SSC08-XII-5, Logan, UT, August 2008

Finally, a paper entitled *The Creation and Impact of Corporate Mentorship on Student-Led Satellite Projects* by Davis, Grusin, Helgesen and Koehler was written for the Small Satellite conference. The main premise of the paper concerned professional mentorship. According to the paper, the team's students have found that professional mentorship is a critical part of the learning experience. It has resulted in an increased motivation to succeed, and a more comprehensive level of real-world thinking when designing satellites. The University of Colorado team has planned from the beginning to pair each subsystem discipline with an industry mentor.

This paper describes the philosophy and implementation used by the University of Colorado student satellite team in establishing professional mentorships and presents the business perspective from a participating corporation. In addition, it proposes that this program-wide methodology can be beneficial to other university teams working in technical fields.

This paper is attached to the end of this report.
Davis, B., Grusin M., Helgesen, B., Koehler, C., The Creation and Impact of Corporate Mentorship on Student-Led Satellite Projects, 22nd Annual AIAA/USU Conference on Small Satellites, SSC08-XII-5, Logan, UT, August 2008

## 3. Collected and Computed Data

This section represents the most significant data finding from the tests on the DANDE satellite subsystems. All these tests have been completed to advance the engineering progress and understanding of this system. The scientific data of merit has yet to be taken since it can only occur while DANDE is on orbit.

### 3.1. In-situ Neutral Density Measurements, Atmospheric Science

Neutral density measurements are obtained by first precisely characterizing the spacecraft's coefficient of drag, cross-sectional area, and mass. A near-spherical shape is optimal for maintaining a constant cross sectional area regardless of attitude and the coefficient of drag for spheres has been well studied during the first phase of the DANDE project [5]. Because of this, it is an ideal shape for reducing uncertainties from this variable of equation 1. Furthermore, the spacecraft velocity must be known to around 0.01 km/s in order to recover density variations from equation 1. This accuracy will be obtained from precise-orbit determination and high-task tracking provided by AFSPC/A9A. To relate the direction of the accelerometer axis to the velocity vector, the attitude of the spacecraft will be determined to approximately 3° of accuracy. The spacecraft will be spin-stabilized to the orbit-normal axis. In addition, the DANDE spacecraft will identify the wind induced acceleration from that induced by density fluctuations by flying a mass spectrometer capable of measuring the wind speed and direction. Finally, the spacecraft will measure the acceleration to a precision of 10 nano-g or better in the direction of the velocity vector. According to error analysis, these accuracies will allow DANDE to recover 2% to 3% density fluctuations in the amplitude of the day-night density variation cycle at solar maximum (2009-2012). The mass-spectrometer on the DANDE spacecraft will also be used to analyze atmospheric composition. Specifically, molecular nitrogen and atomic oxygen levels will be measured to infer additional density data, adjust the coefficient of drag accordingly, and provide additional science. This combination of instrument data has never been flown in orbit before and can shed light on some properties of our neutral atmosphere which are not yet understood or poorly characterized ultimately leading to improved models and better orbit determination.

### 3.2. NMS Data

The NMS energy analyzer has been tested at NASA Goddard with the help of Dr. Fred Herrero and an example of this data is shown in Figure 7.

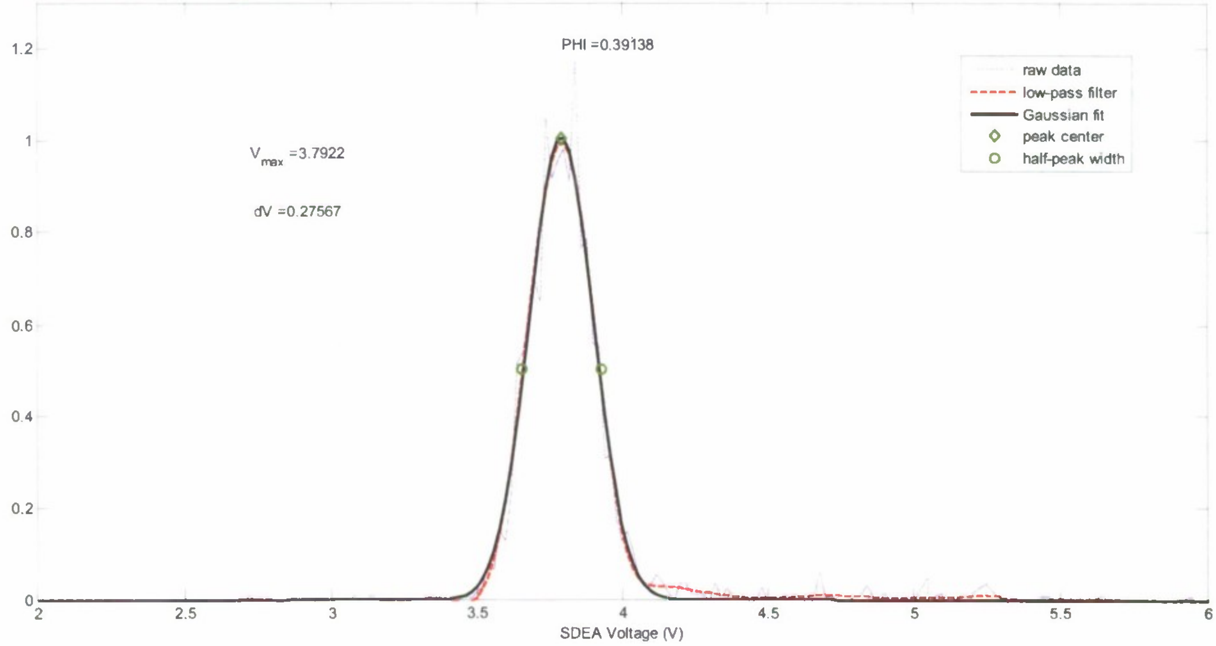



**Figure 7: A mass spectrum collected by the DANDE NMS instrument.**

The estimated precision of wind-speed measured by the NMS instrument is between 5 m/s and 10 m/s. The measured mass resolution is 10%. These measured values meet the science requirements of the DANDE mission.

### 3.3. ACC

The accelerometer subsystem (ACC) has collected simulated rotational data. Each accelerometer head's rotation was simulated and the electronic hardware collected that data. This data was then averaged for each sensor head and the phase offset was used to reduce the data to submicro-g resolutions. The data collection and averaging process is shown in Figure 8. The DANDE coordinates and accelerometer rotation configuration are shown on the left hand side of the figure.

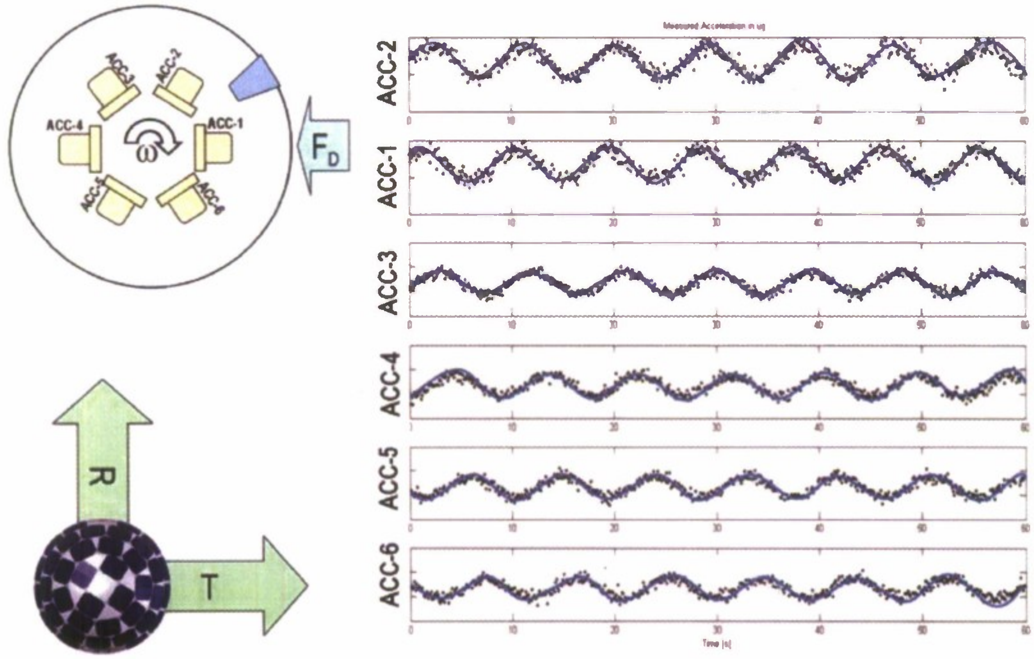



**Figure 8: ACC collected data**

## 3.4. STR

The structure (STR) underwent vibration testing in spring 2008 to determine the capabilities of the design as well as the natural frequencies. An initial sine sweep was conducted to determine the natural frequency of the structure. A sine burst and random vibe were also conducted followed by a sine sweep. The sweep showed whether the natural frequencies changed after the structure was dynamically loaded to ensure that no fundamental modes were excited which lead to failure. Table 3.4-1 shows the different results from the sine sweeps. While the natural frequencies did not significantly change, the Z-axis did see a change in the response loading from 3.30g to 2.90g to 6.65g. This, undesired force along with help from advisors, lead to a redesign of the primary structure which has since become stiffer and stronger.

**Table 3.4-1: Structural vibration results**

| Direction | Natural Frequency (1st Mode) | Sine Sweep | | |
|---|---|---|---|---|
| | | Pre Test | Post Sine Burst | Post Random |
| Z-axis | 232 Hz | 232 Hz<br>3.30g | 232 Hz<br>2.90g | 227 Hz<br>6.65g |
| Y-axis | 84.1 Hz | 84.1 Hz<br>8.30g | 84.1 Hz<br>8.30g | 84.1 Hz<br>8.30g |
| X-axis | 84.9 Hz | 84.9 Hz<br>9.35g | 84.9 Hz<br>9.3g | 84.9 Hz<br>9.3g |

## 3.5. COM

The communications (COM) subsystem has undergone several iterations and tests. The system, which was originally intended to operate at 34,800 bits per second, was rescoped to 9,600 bits per second to be more compatible with many ground stations and radios. While hardware tests have occurred, the primary novel testing concerned antenna testing with the patch antennas designed to contour to the spacecraft's surface. Several anechoic chamber tests have occurred, one of which is shown in Figure 9. The antennas have been a continuing effort and further development and testing remains including long range testing.

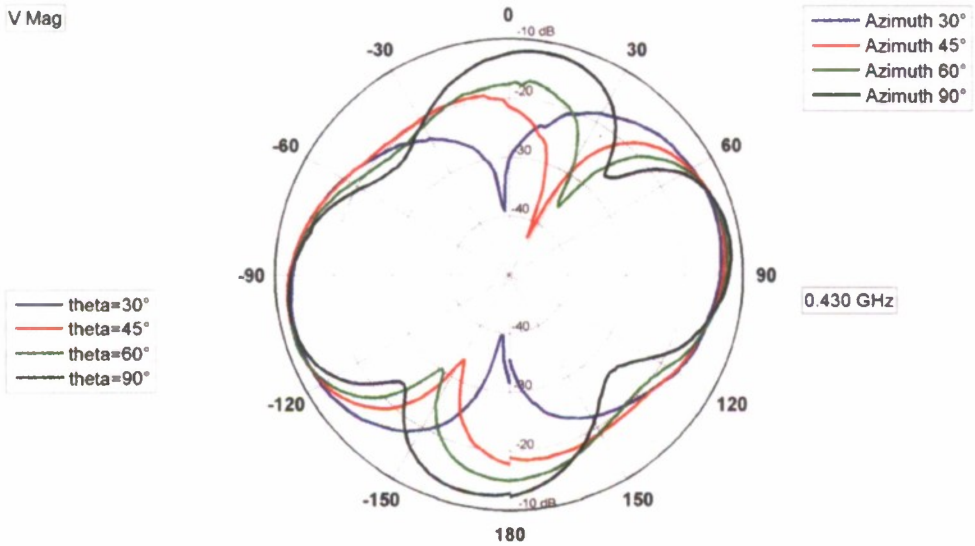



**Figure 9: Patch antenna anechoic chamber test pattern**

## 4. Summary of Work Accomplished

With previous Air Force support, COSGC and the Aerospace Engineering Sciences Department have designed, iterated, tested, and begun integration of the subsystems of the DANDE spacecraft. As a part of this work, students at the university developed the accelerometer subsystem and constructed the Neutral Mass Spectrometer. The spacecraft bus was also designed and built with 75% of the software being ready at the Flight Competition Review on January 20th 2009.

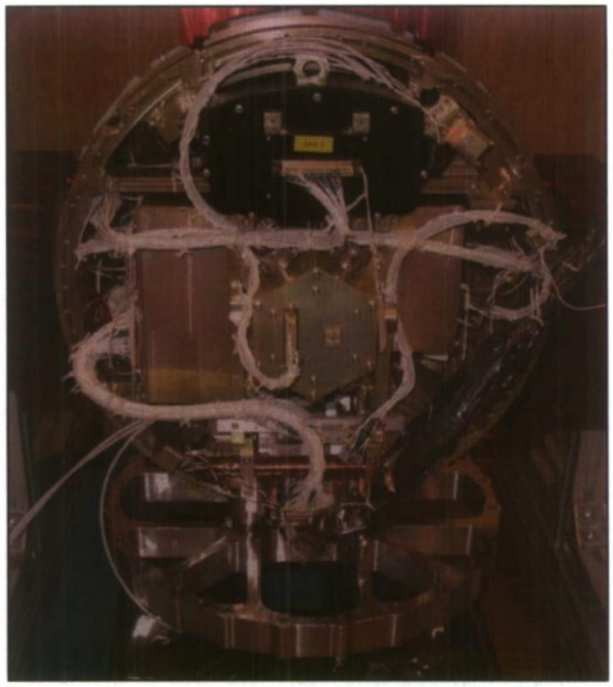


**Figure 10: The DANDE spacecraft has been designed and integrated with previous support from AFOSR.**

## 5. Statement of Work

Final versions of electronic hardware will be completed and purchased this summer. Subsystem software and firmware will be continually worked on and is estimated to be completed by the end of the summer, 2009. The communication system will also be completed by the end of the summer and will have completed anechoic chamber, gain pattern, and long distance testing. The mass spectrometer will also undergo vacuum calibration to validate the design and verify subsystem requirements. DANDE will then be reintegrated and the satellite will progress into the final stage of integrated testing. Final system wide tests include day in the life, vibration, and thermal vacuum.

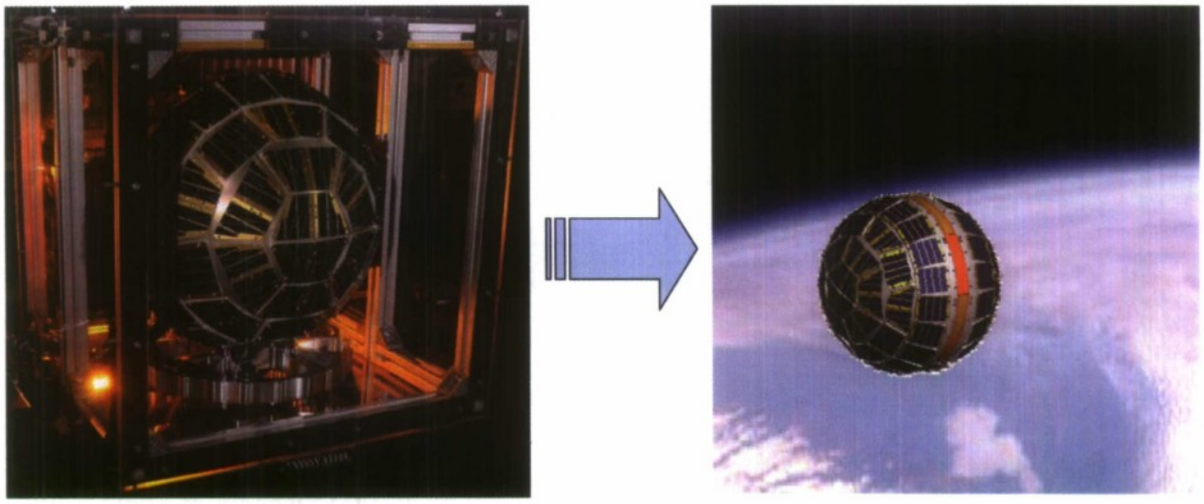


**Figure 11: The scope of this proposal is to prepare the DANDE spacecraft for launch and operations in orbit.**

## 6. Summary

Variations in the drag force on a satellite are directly related to the variations in the neutral atmosphere density. In order to improve upon orbit determination techniques and satellite tracking, it is desirable to have density models which take these variations into account through improved scientific understanding and continuous calibration. Understanding the propagation of disturbances in the neutral atmospheres will increase our understanding of the underlying principles and also help develop better models in the future.

The DANDE mission is a project to improve density and drag modeling in LEO by delivering near real-time neutral density, wind, and composition data at a reduced cost to the Air Force and others as well as by improving the understanding of spatial structures and their dynamics at the 200 to 350 km altitude range. In addition to this, DANDE will improve the resolution of low-cost acceleration measurement techniques and field-test a miniaturized wind and mass-spectrometer.

## 7. References


1. Marcos et. al., "Accuracy of Earth's Thermospheric Neutral Density Models" AIAA 2006-6167, 2006

2. C.F. Minter, et. al., "Advantages of In Situ Data when Estimating the Global Neutral Atmospheric Density Using a Data Assimilation System", University of Colorado, NOAA, Boulder, CO, USA, 2004

3. Ghosh, S. N., The Neutral Upper Atmosphere, Kluwer Academic Publishers, Dordrecht, The Netherlands, 2002

4. Moe et. al., "Method for Deriving Densities and In-Track Winds During Storms", AIAA-2006-6396, 2006

5. Pilinski, Marcin, "Analysis of a Novel Approach for Determining Atmospheric Density from Satellite Drag", M.S. Thesis, University of Colorado, Boulder, 2008

## Appendix A: Theses Resulting from Research

Theses available upon request. Theses total over 500 pages.